

SCIENCE FOR GLASS PRODUCTION

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AN OPTIMUM REGIME FOR GLASS ANNEALING WITH MINIMUM ENERGY CONSUMPTION

B. I. Margolis¹Translated from *Steklo i Keramika*, No. 5, pp. 12 – 13, May, 2003.

Relationships serving as the basis for the calculation of optimum glass-annealing regimes are analyzed. The method for the calculation of optimum cooling regimes is extended to the general case of heat treatment of glass, including the heating, exposure, and cooling stages.

The problems of identifying an optimum regime for glass annealing can be set in two ways. The first consists in minimizing the time the glass article stays in the annealing furnace under limited residual stresses. Such approach is justified in designing new furnaces, which may have a smaller length.

Another setting of the optimum control problem aims for the minimum possible residual stresses in the glass articles under a preset duration of annealing in existing furnaces. However, the important purpose in technology is not to ensure the minimum possible stresses but rather to keep stresses below the admissible values prescribed by regulations (50 – 100 nm/cm for rolled sheet glass and 50 – 200 nm/cm for glass containers). In the general case the annealing process, besides cooling, also includes heating and exposure of glass articles at a preset temperature.

It is important to identify an annealing temperature schedule involving a minimum consumption of energy. This problem can be set as follows: for a preset duration of annealing Δt it is necessary to identify the dependence of the cooling rate on the temperature of the glass article $R(T)$, under which a minimum temperature is achieved in the glass at the end of heating T_{an} , provided that residuals stresses in the glass article do not exceed the permissible level.

The author in [1] obtained a dependence of the cooling rate on the temperature of the glass article that ensures the minimum residual stresses in the article:

$$R(T) = \frac{A}{\Delta t \sqrt{W(T)}}, \quad (1)$$

where $A = \int_{T_h}^{T_l} \sqrt{W(T)} dT$; T_l and T_h are temperatures signifi-

cantly lower and significantly higher, respectively, than the annealing interval.

The temperature of a glass article can be taken as the temperature of a certain surface point (a glass band surface or an angle point on the bottom surface of a cylindrical article). The function $W(T)$ characterizes relaxation processes in the glass and can be taken as the second derivative of the structural temperature.

The structural temperature of a glass-forming material in an equilibrium state ($T \geq T_l$) is equal to the actual temperature and in an isostructural state ($T \leq T_l$) is constant [2]; therefore, the function $W(T)$ outside the annealing interval is equal to zero, which according to expression (1) means infinitely high cooling rates. Consequently, an ideal annealing regime is impossible in practice but can be approached by cooling a glass article outside the annealing interval at the maximum rates possible for the particular furnace.

All the above formulas and expressions are true for what is known as annealing “from above,” when an article enters the furnace with a sufficiently high temperature, under which all emerging stresses relax. In a real process glass often enters the furnace at an insufficiently high temperature corresponding to a nonequilibrium state of the glass-forming material, which prevents it from immediate cooling. Therefore, one should consider the general case of identifying an optimum annealing schedule, which apart from cooling includes stages of heating and exposure of glass articles. One should take into account the restrictions imposed on maximum heating and cooling rates by the properties of the heaters and the lining of the annealing furnace.

For a general case of an optimum annealing schedule the temperature history of a glass article in an annealing furnace should obey the following regularities. First, the glass has to

¹ Tver State Technical University, Tver, Russia.

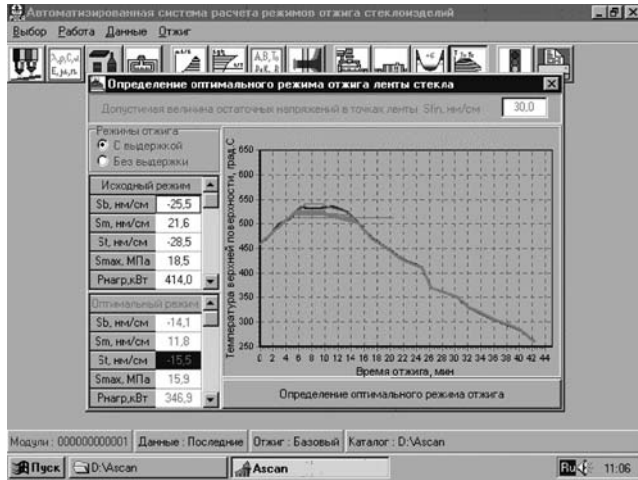


Fig. 1. Optimum annealing regime for rolled sheet glass: S_b and S_t are the residual stresses on the bottom and top surfaces of the glass band, respectively; S_m is the residual stress in the middles of the glass band; S_{\max} is the maximum temporary stress; P_h is the equivalent power of annealing furnace heaters.

be heated from its temperature at the furnace entrance T_i up to the annealing temperature T_{an} with the maximum possible rate for this furnace $R_{H_{\max}}$. The heating stage duration can be found from the formula

$$t_H = \frac{T_{an} - T_i}{R_{H_{\max}}}.$$

Then the article is exposed at the temperature T_{an} for the time t_{exp} required for the relaxation of stresses. The exposure stage ends when temporary stresses stop changing. After that the glass has to be cooled from its annealing temperature to the temperature of exit from the furnace T_f based on a curve determined by the optimum cooling rates $R(T)$ obtained from expression (1) taking into account the restrictions on the maximum cooling rate:

$$R(T) \leq R_{C_{\max}}.$$

For a furnace length l_f and velocity of the article inside this furnace v_{art} the total duration of annealing will be

$$t_{tot} = \frac{l_f}{v_{art}},$$

and the cooling duration will be equal to

$$\Delta t = t_{tot} - t_H - t_{exp}.$$

For the average cooling rate the following relationship has to be satisfied:

$$R_m = \frac{T_{an} - T_f}{\Delta t} \leq R_{C_{\max}}.$$

Otherwise it is impossible to implement the optimum annealing schedule.

It is possible to use the “golden section” method in searching for the minimum temperature to end the heating of the glass article. The left boundary for this search is T_i and the right boundary is a temperature obviously exceeding the vitrification temperature T_h . This method converges to the sought-for T_{an} in 7 to 10 steps. Simulation results revealed that the exposure stage is not necessary, i.e., after the article is heated to T_{an} , it can be immediately cooled according to the optimum curve $R(T)$.

In calculating the optimum cooling curve, it is convenient to make all values discrete, i.e., to determine the values $W(T_i)$ and $R(T_i)$ for $i = \overline{1, m}$; ($R(T_i)$ is the glass cooling rate in the temperature interval from T_i to T_{i+1} ; $m = T_{an} - T_f$; $T_1 = T_{an}$, $T_2 = T_{an} - 1$; ..., $T_m = T_f + 1$). The integral A in formula (1) in this case can be calculated using the trapezoidal rule:

$$A = \frac{\sqrt{W(T_1)}}{2} + \sum_{i=2}^{m-1} \sqrt{W(T_i)} + \frac{\sqrt{W(T_m)}}{2}. \quad (2)$$

In calculating the optimum cooling rates $R(T_i)$ based on expression (1), their values may exceed the maximum rate $R_{C_{\max}}$ that can be implemented in a particular annealing furnace. In this case one should take $R(T_i) = R_{C_{\max}}$ and update the values of the weight function $W(T_i)$ using the formula

$$W(T_i) = \left[\frac{A}{\Delta t \times R_{C_{\max}}} \right]^2.$$

The integral of the root of the weight function A is calculated from Eq. (2). Variation of the cooling rates will make the cooling time calculated for discrete velocities

$$t_{cool} = \sum_{i=1}^m \frac{1}{R(T_i)}$$

different from the required Δt . Accordingly, the values have to be corrected until the difference between the absolute values of t_{cool} and Δt becomes less than a certain value of accuracy.

As an example, let us calculate the optimum annealing schedule for rolled sheet glass at the Krasnyi Mai Glass Works (Vyshnii Volochok). The regime that is optimum for energy saving is shown in Fig. 1.

The optimum regime was calculated using the automated system for calculation of glass-annealing schedules [3] for the following initial conditions: $T_i = 450^\circ\text{C}$, $T_f = 250^\circ\text{C}$, $l_f = 61.8 \text{ m}$, $v_{art} = 1.2 \text{ m/min}$; $R_{H_{\max}} = 15 \text{ K/min}$; $R_{C_{\max}} = 10 \text{ K/min}$.

Using the optimum schedule allows for 8 – 10% saving in energy consumed in glass band annealing while maintaining the required quality level. The equivalent power of the heaters in this case is reduced due to a shortening of the glass exposure, whereas smoother cooling in the critical annealing zone facilitates a decrease in residual stresses.

REFERENCES

1. O. S. Narayanaswamy, "Optimum schedule for annealing flat glass," *J. Am. Ceram. Soc.*, **64**, 109 – 114 (1981).
2. O. V. Mazurin, *Vitrification* [in Russian], Nauka, Leningrad (1986).
3. B. I. Margolis, "Structure of an automated system for calculation of annealing regimes for glass articles," *Steklo Keram.*, No. 4, 3 – 5 (2003).